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## 2. Results of Literature Search on Dielectric Properties and Electron Interaction Phenomena Related to Spacecraft Charging

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### 1. INTRODUCTION

#### 1.1 Background

It has been known for over two decades that electron irradiation of insulators can produce an accumulation of charge sufficient to cause dielectric breakdown. The first published description of this effect appears to be due to Gross<sup>1</sup> who investigated dielectric breakdown produced by 2 MeV electrons in Plexiglass. This and subsequent publications on electron induced breakdown by Gross and others (see bibliography) contained only qualitative or semi-quantitative descriptions of the phenomenon. Also, electrons with energies greater than 1 MeV were generally used to induce breakdown. Consequently, when the possibility that the problem of spacecraft charging could be due to a similar effect was considered, that is, that space-plasma electrons incident on the dielectric materials used on the exterior of satellites could cause charge buildup and subsequent dielectric breakdown,

1. Gross, B. (1958) Irradiation effects in Plexiglass, J. Polymer Sci. 27:135.

a literature search was begun to determine how much information was currently available on the interaction of electrons with energies comparable to those encountered in space. In addition, the search was to cover information that might be useful in obtaining a more quantitative description of electron induced breakdown.

The literature search was originally intended to form the basis of an experimental program with the objective of determining the required material properties and electron interaction parameters needed for modeling charge buildup and breakdown in insulators. However, it was found that a number of publications had appeared in recent years in which electrons with energies in the 1 to 50 keV range had been used to investigate insulator properties such as conductivity and charge storage. As the search continued it was found that much of the data needed appeared to be available in the literature, but it was scattered among reports related to various interests ranging from fundamental properties of insulators to engineering applications such as electrophotography and electrets. Also, results obtained for specific properties and parameters varied widely among different authors. It was therefore decided that the literature search should be continued in depth in order to evaluate and correlate the available data prior to initiating an experimental program.

Only a brief overview of the results of the literature search can be given here. A partial list of the references covered is included in a bibliography at the end of the paper to enable the reader to obtain more complete coverage of particular areas of interest. Although inorganic insulators were also considered in the search, we limit coverage in this paper to the organics, primarily Kapton and Teflon, for the sake of brevity.

## 1.2 Factors Covered in Literature Search

Figure 1 illustrates the electron interactions related to charge buildup in insulators. Energetic electrons incident on the insulator penetrate the surface of the material. Some of the electrons undergo elastic (Coulombic) collisions with the constituent atoms and are "backscattered" out of the material. The remaining electrons interact inelastically with the orbital electrons of the atoms generating electron-hole pairs by ionization as they lose energy and eventually slow to thermal energy near the end of their maximum range in the material. (Interactions such as significant x-ray production, atomic displacements, etc., are neglected here.) Some of the electrons produced by ionization escape from the surface of the material as secondary electrons and these, along with the backscattered electrons, reduce the net excess charge that enters the material from the initial incident electron flux. The remaining electron-hole pairs and the thermalized incident electrons act as current-carriers, producing a region of enhanced (radiation induced) conductivity in that portion of the insulator included in the range of the incident electrons. The

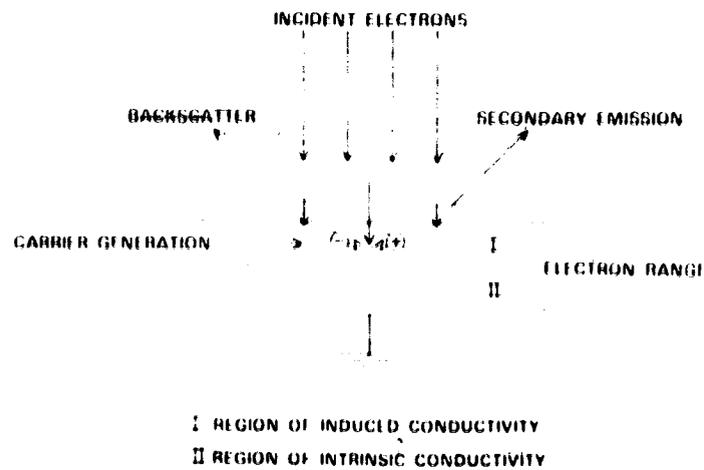


Figure 1. Electron Interactions Related to Charge Buildup in Insulators

time integral of the net electron current penetrating the insulator is the charge accumulated by the insulator. This charge can drift under the influence of its own field, or image forces, toward an electrode attached to the material. If it cannot drift and be removed from the insulator at a sufficient rate, charge buildup can occur producing an electric field strong enough to cause dielectric breakdown. In the configuration shown in Figure 1 for example, the charge would have to drift through the region of intrinsic conductivity to be removed from the insulator. The intrinsic conductivity of most good insulators, such as Kapton and Teflon, is much too low to permit a sufficient rate of drift to prevent charge buildup. In some materials, however, it may be possible to take advantage of the region of radiation induced conductivity by applying an electrode to the surface of electron incidence to remove the excess charge.

From the above brief description of the processes involved in electron-induced charge buildup in insulators it can be seen that the factors that needed to be covered in the literature search were:

- (1) Conductivity (including thermal, high-field, and radiation effects),
- (2) Secondary electron emission,
- (3) Electron range and rate of energy loss.

In addition to these, dielectric breakdown processes were also covered in the search.

## 2. CONDUCTIVITY

### 2.1 Parameters Needed to Characterize Conductivity in Insulators

The energy band model, used to describe conduction processes in crystalline solids such as semiconductors, has generally been adapted to apply to amorphous materials such as organic (and most inorganic) insulators. Consequently, the expression for the conductivity of an insulator is given as

$$\sigma = e(n_+ \mu_+ + n_- \mu_-) \quad (1)$$

where  $\sigma$  is the conductivity,  $e$  the electron charge,  $n_{\pm}$  the concentration of holes (+) or electrons (-) in the conduction band and  $\mu_{\pm}$  the corresponding mobility. (Here we neglect the possibility of current transport by hydrogen nuclei considered by some authors as charge carriers in organic materials.) Because organic insulators contain a high concentration of trapping centers distributed in energy between the valence and conduction bands, the mobilities in Eq. (1) cannot be interpreted as simply as they can, for example, for semiconductors. For the insulators, conduction is usually described as a "trap-hopping" process in which the carriers move from one trapping center to another, remaining for a finite time at each center. Values of mobility are therefore usually given as time-averages, called the trap-modulated mobility. The value of the trap-modulated mobility is a function of the number of available traps, that is, it depends on the number of trapping centers that are occupied. Consequently, it is a function of the number of excess carriers injected into the insulator as well as temperature, electric field, and time.

In addition to the charge carrier mobilities, values of the following parameters are needed to model conductivity in insulators:

- (1)  $n$ : The concentration of potentially available charge carriers, that is, trapped plus mobile charges. This includes intrinsic carriers as well as those injected from external sources.
- (2)  $W_x$ : The activation energy of parameter  $x$  for

$$x = x_0 \exp(-W_x/kT) \quad (2)$$

where  $k$  is Boltzmann's constant,  $T$  the absolute temperature and  $x$  is a parameter such as the concentration of carriers in the conduction band, mobility, or a combination of parameters such as conductivity. It is not

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Some authors give values of mobility for carrier transport between traps and these can be several orders of magnitude greater than the trap-modulated mobilities. In using these values of mobility Eq. (1) must be modified to include trapping parameters.

always clear from a given paper to which factor the author intended the activation energy to apply, but its value is frequently reported since most of the parameters related to conductivity show the exponential form of Eq. (2) over a range of temperatures.

(3)  $N_t$ : The concentration of trapping centers.

(4)  $E_t$ : The energy, or depth, of trapping centers. This along with  $N_t$  (as a function of  $E_t$ ) gives the trap distribution in an insulator. Frequently, however, a "single trapping level" model is used which assumes that all traps are concentrated at a single level. In this case the value of  $E_t$  reported is actually a weighted average over  $N_t$ .

(5)  $\tau$ : Carrier lifetime between traps. This parameter may also appear in the literature as the time spent by a carrier in traps. It is not always clear which meaning a particular author has given to  $\tau$ . Another form of this parameter is the recombination coefficient, designated by various symbols, that measures the fraction of carriers that remain free per unit time.

(6)  $\eta$ : The number of carrier pairs generated per incident electron (or photon). This parameter is related to radiation induced conductivity. Another quantity frequently used instead is the energy that must be dissipated in the material by an electron or photon to produce a single carrier pair.

Although there are other parameters used in modeling conductivity, some of which are alternates for—or combinations of—the above, those listed are the most frequently encountered in the analysis of conduction processes in insulators. It should be noted that the symbols used in the literature for various parameters are by no means uniform. Those used here are probably the most commonly encountered.

## 2.2 Methods Used to Measure Conductivity Parameters

The method used to measure a particular conductivity parameter can significantly affect the value obtained. This is due, at least partly, to the fact that the technique used to measure the parameter may affect the insulator in a way that cannot be accounted for in the model used to interpret the results of the measurement. When taking the value of a parameter for insulator conductivity from the literature, therefore, it is important to be aware of the method used to measure it in order to evaluate its validity for the application intended.

Figure 2 shows schematically four methods used to determine conductivity parameters for organic insulators. Part (a) of the Figure shows the "classic" method used to measure conductivity. Electrodes are pressed, painted, or evaporated onto two opposite surfaces of the sample. A potential,  $V$ , is applied to the electrodes and the current,  $I$ , through the insulator is measured by meter  $M$ . The

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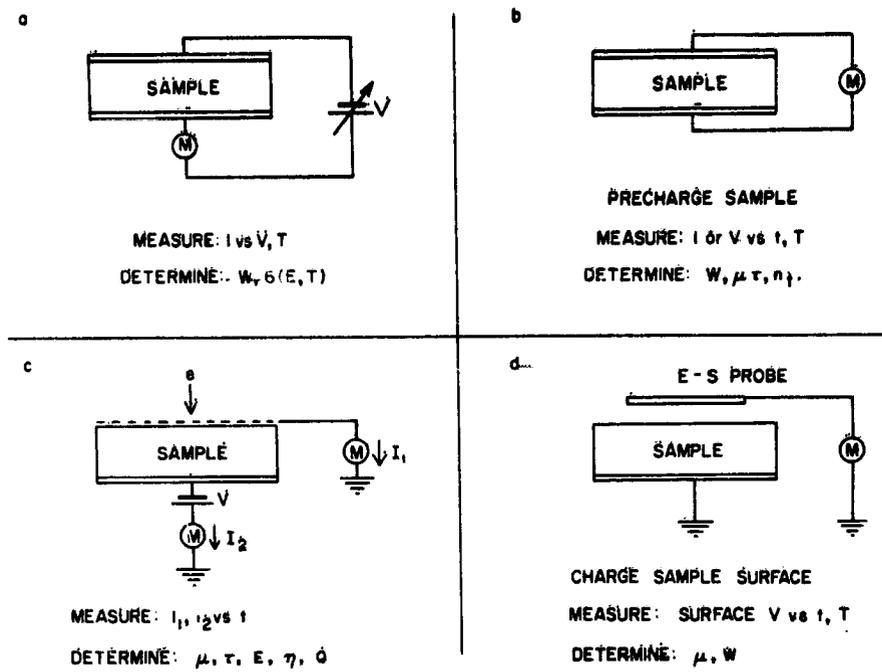


Figure 2. Methods Used for Measuring Conductivity Parameters in Insulating Materials

conductivity can then be calculated from the ratio of  $I$  to  $V$  and the dimensions of the sample. By varying the applied potential and the temperature, the conductivity as a function of electric field ( $E$ ) and temperature ( $T$ ) can be obtained. From this data an activation energy,  $W$ , for conductivity can be derived. The problem with this method is that the electrodes can have a significant affect on the results obtained. Lilly and McDowell<sup>2</sup> used this method to measure the conductivity in Mylar and Teflon. They found that their results did not agree with theories of current injection from the electrodes which must be accounted for in measurements of this type.

The procedure illustrated in part (b) of Figure 2 reduces some of the electrode effects by using the electrodes as charge collectors instead of sources of current carriers during the measurement. The sample is precharged either before or after application of the electrodes by exposure to an electron beam, a corona discharge or application of a potential. The charging source is removed and a meter attached to the electrodes to measure either the potential between the electrodes or the current (charge) released by the insulator as a function of time and temperature. The resultant data can then be used to determine parameters such as activation

2. Lilly, A. C., Jr., and McDowell, J. R. (1968) High-field conduction in films of Mylar and Teflon, J. Appl. Phys. 39:141.

energy, the product of mobility and carrier lifetime, and the number of initially trapped carriers ( $n_t$ ). Perlman and Unger<sup>3</sup> used this method with electron-charged samples to measure trap densities in Teflon.

Part (c) of Figure 2 shows a method that has recently been used fairly extensively because of its versatility and reliability. An electron beam with insufficient energy to fully penetrate the sample is used to supply charge to the insulator. The electrode on the surface of electron incidence is thin enough to be transparent to the electrons. The applied potential,  $V$ , is usually low enough (it may be zero) to minimize carrier injection from the electrodes. Observation of the currents  $I_1$ , which originates from the region of radiation induced conductivity (see Figure 1), and  $I_2$ , which is the net sample current including that in the non-irradiated region, as functions of time, yields values for the mobility, carrier lifetime, the average electric field ( $E$ ) in the insulator, the number of carrier pairs produced per incident electron and the stored charge. Details of this method have been analyzed by Gross, Sessler, and West.<sup>4</sup>

The method illustrated in part (d) of Figure 2 reduces electrode and other extraneous effects to a minimum. The sample has a grounded electrode on one surface only. A charge is deposited on the surface of the sample and the surface potential measured as a function of time with a non-contacting electrostatic probe (E-S). The surface potential decreases in time as the charge drifts through the insulator under the influence of its own field and image forces due to the presence of the grounded electrode. The resultant data can be used to calculate the intrinsic mobility of the charge carriers deposited on the sample. The activation energy for the mobility can be obtained by repeating the measurement at different temperatures. This procedure was introduced by Davies<sup>5</sup> to investigate static charge decay in polyethylene and glass. It was further developed by Batra et al<sup>6</sup> for the analysis of materials used in electro-photography. It has recently been applied to other insulating materials because it is perhaps the best method currently available that can give an unambiguous measure of carrier mobility in very low-conductivity materials.

### 2.3 Carrier Mobilities in Teflon

Although many of the parameters used in modeling conductivity have been measured for a variety of insulators it is not possible to consider all of them here.

3. Perlman, M. M., and Unger, S. (1972) TSC study of traps in electron-irradiated Teflon and Polyethylene, J. Phys. D 5:2115.
4. Gross, B., Sessler, G. M., and West, J. E. (1974) Charge dynamics for electron irradiated polymer-foil electrets, J. Appl. Phys. 45:2841.
5. Davies, D.K. (1967) 1967 Static Electrification Conference Institute of Physics and the Physical Society, London, p. 29.
6. Batra, L. P., Keiji Kanazawa, K., and Seki, H. (1970) Discharge characteristics of photoconducting insulators: J. Appl. Phys. 41:3416.

even for one material. This is because of the diversity of values of some of the parameters reported for a given material as well as the fact that all authors do not present the values they obtain in the same way. For example, carrier lifetime, as indicated in Section 2.1, can be reported with different (but equivalent) physical meanings and its value may be reported as a single value or as the coefficient of an exponential function associated with an activation energy. The purpose of this section is to illustrate this diversity of values and show that one should not simply accept a value for a given parameter from the literature without first evaluating its source. To do this, we have chosen the values of mobility for charge carriers found in the literature for Teflon as an example. Table 1 shows some of the mobility values found.

Table 1. Values of Carrier Mobility in Teflon

Mobility ( $\text{cm}^2/\text{V}\text{-sec}$ )	Comments
$2 \times 10^{-12}$	Hole from 0.7 eV trap
$7.6 \times 10^{-14}$	Hole from 1 eV trap
$7.4 \times 10^{-22}$	Electron from 1.8 eV trap
$1.3 \times 10^{-9}$	Electron Charged sample
$\leq 4 \times 10^{-10}$ $\sim 5 \times 10^{-17}$	Electron induced conductivity Room temperature, non-irradiated
$5 \times 10^{-4}$ $5 \times 10^{-5}$	Hole, pulsed electrons Electron, pulsed electrons

The first three mobility values are from a recent paper by Sessler and West.<sup>7</sup> They used the open-circuit method shown in part (d) of Figure 2, precharging the sample by application of a voltage to the open surface of the sample before starting the measurement. The temperature was raised from about 20 to 200°C during the surface potential measurements. This gave mobility as a function of temperature from which the activation energies (shown in Table 1 as trap levels in eV) of mobility were derived. The values of mobility shown in Table 1 were derived from a plot of mobility vs temperature given in the paper and were extrapolated to room temperature (300°K) for comparison with the other values shown. It is clear from these results that holes are the predominant charge carrier in Teflon.

7. Sessler, G.M., and West, J.E. (1976) Trap-modulated mobility of electrons and holes in Teflon FEP, J. Appl. Phys. 47:3480.  
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The fourth value of mobility shown is from a paper published a few months earlier by Gross, Sessler, and West.<sup>8</sup> The sample was electron irradiated as in method (c) of Figure 2, raising the temperature from room temperature to 250°C. It is not clear from the paper at what temperature the value of mobility reported applies. The authors attribute the higher value of mobility (they reference unpublished work of Sessler and West, which is probably our Reference 7 that had not yet been published) to a greater concentration of electrons obtained by irradiation instead of voltage-charging the sample. Although the sign of the carriers was not determined, they were assumed to be holes injected by image forces from the electrode adjacent to the non-irradiated region of the Teflon, and assume the higher value of mobility was obtained because more traps were filled in the sample.

The next two values of mobility in Table 1 were also determined by Gross, Sessler, and West<sup>4</sup> using method (c) of Figure 2, but without changing the sample temperature. Approximate values for some parameters were used to calculate the mobility from the data, thus the "less than or equals" sign before the value given. The estimated mobility in the non-irradiated region of the sample was derived from charge-decay estimates and the authors state that the value obtained is probably too low.

The last two values of mobility in Table 1 were obtained by Hayashi et al.<sup>9</sup> using pulsed electrons in a modified version of method (c) of Figure 2. In the model used to interpret their data, they assumed that both electrons and holes could act as charge carriers. This may account for the much higher values of mobility they report.

From the example given, it can be seen that in selecting a parameter for modeling conductivity in an insulator, one must be very careful to evaluate not only the method used to obtain it but also the authors' interpretation of the data. Lacking a better basis on which to judge the parameter values available, it is probably best to select a value that has been measured by a method most closely resembling the application one has in mind for the data.

#### 2.4 Temperature Dependence of Conductivity

The temperature dependence of conductivity for most insulators usually follows the exponential form

$$\sigma = A \exp(-W/kT) \quad (3)$$

8. Gross, B., Sessler, G. M., and West, J. E. (1976) TSC studies of carrier trapping in electron- and  $\gamma$ -irradiated Teflon, J. Appl. Phys. 47:968.
9. Hayashi, K., Yashino, K., and Inuishi, Y. (1973) Mobility measurements in polymers using pulsed electron beams. 1973 Conference on Electrical Insulation and Dielectric Phenomena (National Academy of Sciences, 1974), pp 424-430.

near and above room temperature. Here, A and W are empirical constants. As in Eq. (2) of Section 2.1, W is the activation energy of conductivity. Starting at lower temperatures (for example, near 80°K) different values of W are found as the temperature is raised, corresponding to the emptying of different trap levels. (Actually this occurs above room temperature also, but is not usually observed except in very carefully controlled experiments.)

The temperature dependence of conductivity is usually measured by the method shown in part (a) of Figure 2. As mentioned in the discussion of that method (Section 2.2) the electrodes applied to the sample can influence the results obtained. The material used for the electrodes, the nature of the contact (ohmic, blocking, etc.) made with the insulator, and effects such as Schottky emission (essentially the thermionic emission of carriers from the electrodes into the insulator) must be considered in the measurement. Because of difficulties in evaluating the electrode effects, theoretical values of A and W are not usually in good agreement with experiment.

The values obtained for A and W also depend on the sample thickness and the potential used in the measurements because the conductivity of most insulators is a function of the electric field applied. For example, with an applied field of approximately  $5 \times 10^4$  V/cm, Amborski<sup>10</sup> found the activation energy for Kapton to be about 1 eV. Hanscomb and Calderwood<sup>11</sup> measured the current passed by samples of Kapton as a function of both applied field and temperature. They extrapolated their data to zero applied field and found the activation energy to be 1.55 eV. (No comparison can be made between the values of A for these two papers because of insufficient data.)

### 2.5 Electric Field Dependence of Conductivity

The conductivity of insulators as a function of applied electric field has been measured by a number of authors, many of whom developed theories to explain their data. Adamec and Calderwood<sup>12</sup> developed the following relationship for the relative conductivity of insulators as a function of applied field:

$$\sigma/\sigma_0 = \frac{2 + \cosh(\beta F^2/2kT)}{3} \quad (4)$$

where

10. Amborski, L. E. (1963) H-film—a new high temperature dielectric, Ind. and Eng. Chem. -Prod. R and D 2:189.
11. Hanscomb, J. R., and Calderwood, J. H. (1973) Thermally assisted tunnelling in polyimide film under steady-state and transient conditions, J. Phys. D 6:1093.
12. Adamec, V., and Calderwood, J. H. (1975) Electrical conduction in dielectrics at high fields, J. Phys. D 8:551.

$$\beta = (e^3 / \pi \kappa \epsilon_0)^{1/2} = 1.216 \times 10^{-23} \kappa^{-1/2}$$

$\kappa$  = dielectric constant of the insulator,  
 $e$  = electron charge,  
 $\epsilon_0$  = permittivity of vacuum,  
 $F$  = applied field in V/m,  
 $\sigma_0$  = insulator conductivity at zero applied field.

They compared this expression with theories developed by six other authors to show that it gave the best fit to data for Kapton, Mylar, Polyethylene, and other insulators.

Figure 3 is a plot of the relative conductivity of Kapton vs applied field calculated from Eq. (4) compared with measurements from Reference 12. As can be seen from the plot, agreement between theory and experiment is very good. Similarly good agreement was obtained for the other insulators for which comparisons were made.

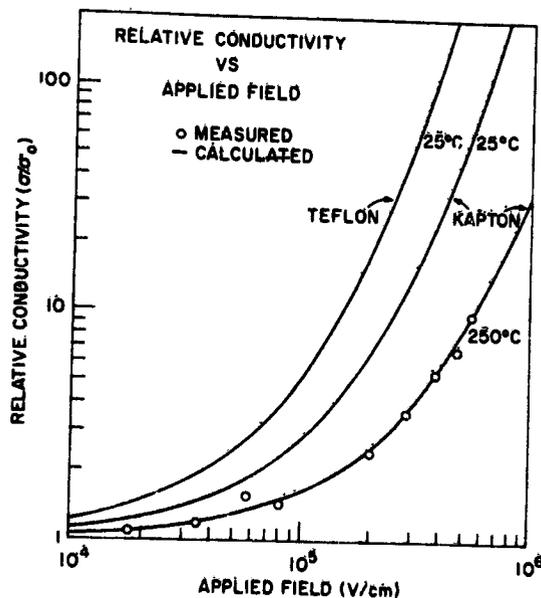


Figure 3. Dependence of the Conductivity of Kapton and Teflon on Electric Field. Kapton data taken from Reference 12. Solid curves calculated from Eq. (4)

Because of the low conductivity of Kapton at room temperature, the data shown in Figure 3 was taken at 250°C. For comparison, we used Eq. (4) to calculate the field dependence of conductivity for Kapton at 25°C. The results are also plotted in Figure 3 along with the results of a similar calculation for Teflon.

## 2.6 Radiation Induced Conductivity

The generally accepted expression for the increase in conductivity induced in an insulator by energetic radiation is

$$\sigma - \sigma_0 = K D^\Delta \quad (5)$$

where

- $\sigma_0$  = the intrinsic conductivity,
- $\sigma$  = conductivity during irradiation,
- $D$  = dose rate,
- $K, \Delta$  = constants.

Although in principle the constants  $K$  and  $\Delta$  can be predicted theoretically, empirical values are invariably used. Theory predicts that  $K$  and  $\Delta$  should be independent of the type and energy of the radiation (that is, electrons, gamma- or x-rays), but the empirical values reported differ among various authors by too great a range to confirm this. The reasons for the differences are not clear, but as with other measurements on insulators, particularly polymers, it could involve electrode effects, thermal effects, etc., as well as changes in material properties caused by radiation damage during the measurements. However, the constant  $K$  is the more significant of the two because  $\Delta$  is the most frequently found to be within 10 percent of unity. Errors in  $\Delta$  therefore have relatively little effect on the magnitude of the induced conductivity calculated from Eq. (5).

To illustrate the differences that can occur in the value of  $K$ , Table 2 shows the range of  $K$  found in the literature for some of the polymers.

Table 2. Range of Values of  $K$  in Units of  $\text{sec}/\Omega\text{-cm-rad}$ .

Material	$K_{\text{max}}$	$K_{\text{min}}$
Kapton	$6 \times 10^{-18}$	$1.2 \times 10^{-19}$
Teflon	$1 \times 10^{-16}$	$2 \times 10^{-18}$
Mylar	$2.1 \times 10^{-19}$	$1.8 \times 10^{-19}$
Polyethylene	$4.5 \times 10^{-18}$	$3 \times 10^{-19}$
Polystyrene	$1 \times 10^{-16}$	$2 \times 10^{-18}$

As with other parameters associated with insulators, it is probably best to select a value of  $K$  from the literature that was determined under conditions most

closely related to the application intended for the data. For upper and lower limit calculations, the appropriate maximum or minimum value should be used.

### 3. ESTIMATION OF ELECTRIC FIELD DEVELOPED DURING ELECTRON IRRADIATION OF AN INSULATOR

Analysis of charge transport in electron-irradiated polymers in some recent papers has suggested the following application of radiation induced conductivity data. While measuring electron induced conductivity in polyethylene terephthalate, Beckley et al.<sup>13</sup> experienced difficulties with frequent electrical breakdowns of their samples. They used an analysis based on work by Nunes de Oliveira and Gross<sup>14</sup> to show that the breakdowns could be caused by fields built up by differential charging of the insulator during irradiation. Beckley and his coworkers based their calculations on a somewhat more obscure form of the original relationships developed by Nunes de Oliveira and Gross. We use the expressions from the paper by the latter authors to illustrate the procedure for Kapton and Teflon.

Referring to Figure 1, assume that a grounded electrode is located on the surface of electron incidence of the insulator as well as on the opposite surface. After correcting for secondary emission and backscatter, take the net current entering the insulator to be  $I_0$ . Assuming no current flows in the non-irradiated region of the insulator (region II of Figure 1), at equilibrium the field in the irradiated region (region I of Figure 1) will be

$$F_1 = I_0 / \sigma_i \quad (6)$$

where  $\sigma_i$  is the radiation induced conductivity, since the current entering the region must equal the current leaving (by Kirchoff's law). (Note that we have ignored the direction of the current flow, and therefore the field, which would have no relation to the occurrence of breakdown.) The dose rate in rad/sec in region I is

$$\dot{D} = (dE/dx) \times 10^{11} I_0 \quad (7)$$

where  $dE/dx$  is the rate of energy loss of the electrons in  $\text{MeV-cm}^2/\text{g}$  and  $I_0$  is in amperes. Combining Eq. (5) for the radiation induced conductivity (neglecting  $\sigma_0$  and taking  $\Delta = 1$ ) with Eqs. (6) and (7) gives

$$F_1 = 1 / (dE/dx) \times 10^{11} K \quad (8)$$

13. Beckley, L. M., Lewis, T. J., and Taylor, D. M. (1976) Electron-beam-induced conduction in polyethylene terephthalate films, J. Phys. D 9:1355.
14. Nunes de Oliveira, L., and Gross, B. (1975) Space-charge-limited currents in electron irradiated dielectrics, J. Appl. Phys. 46:3132.

Since the potential across the sample is zero

$$F_1 R = F_2 (D - R) \quad (9)$$

where  $R$  is the electron range and  $D$  the sample thickness. The field in the non-irradiated region,  $F_2$ , is therefore

$$F_2 = F_1 R / (D - R) . \quad (10)$$

Figure 4 shows plots of  $F_1$  and  $F_2$  vs electron energy for a range of thicknesses of Kapton and Teflon. The values of  $K$  used to calculate the plots were taken from Weingart.<sup>15</sup> These  $K$  values are relatively low so that an upper limit estimate of the field is obtained (for Kapton,  $K = 1.2 \times 10^{-19}$  sec/ $\Omega$ -cm-rad and for Teflon  $K = 3.1 \times 10^{-18}$  sec/ $\Omega$ -cm-rad). As can be seen from the plots, breakdown is most likely to occur at the surface of electron incidence. The field in Kapton approaches the breakdown range of the order of  $10^6$  V/cm much more rapidly than the field in Teflon. However, Teflon has a lower dielectric strength than Kapton and Gross et al.<sup>16</sup> have shown that breakdown may occur in electron irradiated Teflon at least a factor of 2 below the published dielectric strength. If there is a significant current flow in the non-irradiated region of the insulator due, for example, to field enhanced conductivity which has been neglected here, the fields calculated from Eqs. (8) and (10) would be reduced by the factor  $(1 - I/I_0)$ , where  $I$  is the current in the non-irradiated region.

These calculations should be understood to give only rough estimates of the fields built up in insulators during electron irradiation since several factors that could affect the results have been neglected. For example, charge drift during the transient period before equilibrium is reached has been ignored, as well as possible radiation effects, image forces at the electrodes, the previously mentioned field enhanced conduction, etc. However, the procedure is a simple way of evaluating materials regarding their relative tendency to break down during electron irradiation and shows that making both surfaces of an insulator conducting will not necessarily prevent breakdown.

15. Weingart, R. C., Barlett, R. H., Lee, R. S., and Hofer, W. (1972) X-ray induced photoconductivity in dielectric films, IEEE Trans. Nuc. Sci. NS-19(No. 6):15.
16. Gross, B., Sessler, G. M., and West, J. E. (1973) Conduction and breakdown in polymer foils charged by electron irradiation. 1973 Conference on Electrical Insulation and Dielectric Phenomena (National Academy of Sciences, 1974), p. 485.

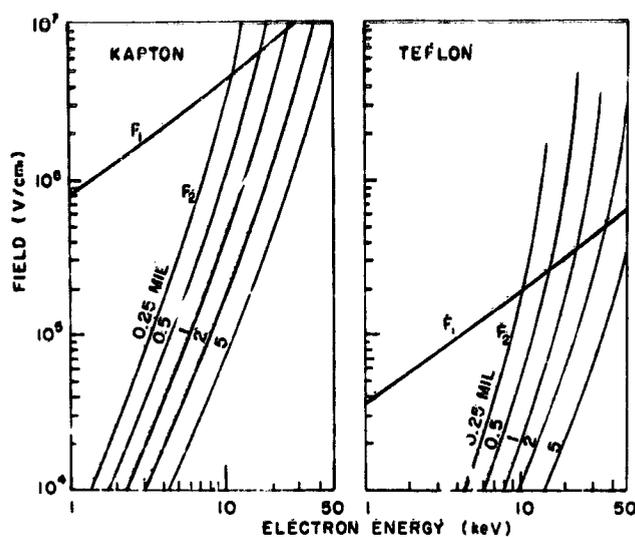


Figure 4. Estimated Equilibrium Electric Fields in Kapton and Teflon Resulting From Electron Irradiation. Grounded conductive coatings on both surfaces of sheets of the materials with thicknesses indicated.  $F_1$  is the field in the region between the surface of electron incidence and the electron range.  $F_2$  is the field in the non-irradiated region which is assumed to be non-conducting. The curves for  $F_2$  in Teflon terminate near the energy at which the electron range exceeds the insulator thickness

#### 4. SECONDARY EMISSION

Because of its practical applications, secondary emission has long been a subject of investigation. As a result, a considerable volume of data exists covering many materials including organic and inorganic insulators. Although not all incident electron energies of interest have been covered for all materials, sound theoretical and semi-empirical relationships have been developed that can be used to extend the available data. An example of such a relationship is the "universal secondary emission curve". It is given by

$$\frac{\delta}{\delta_m} = \frac{g_n(x_m E/E_m)}{g_n(x_m)} \quad (11)$$

where

$$g_n(x) = [1 - \exp(-x^n)] / x^{n-1}$$

$\delta$  = secondary emission coefficient,

$\delta_m$  = maximum value of  $\delta$ ,

$E$  = incident electron energy,

$E_m$  = value of  $E$  at which  $\delta_m$  occurs,

$x_m$  = value of  $x$  for which  $g_n$  has a maximum.

For a given material,  $x_m$  and  $n$  must be determined numerically to fit the available data. Most measured values of the secondary emission coefficient can be fit to the universal curve. In fact, if data is found that cannot be fit to the curve, there were probably errors made during measurement of the coefficient.

Figure 5 shows secondary emission data for Teflon taken from Matskevich<sup>17</sup> fitted to the universal curve. The data was taken from a plot in the paper and deviations of some of the points from the curve are probably due as much to reading the plot as to experimental error.

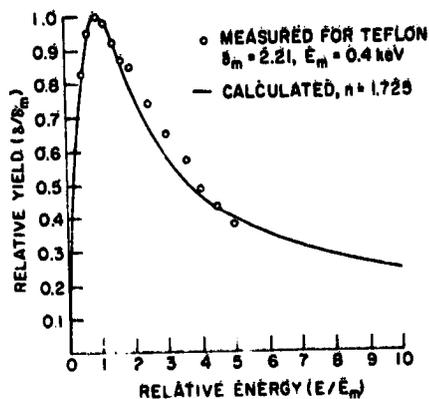


Figure 5. Universal Secondary Emission Curve for Teflon Fitted to Data Taken From Reference 17

For electron energies above about 0.5 keV, the following empirical relationship holds well:

$$\delta = KE^{-m} \quad (12)$$

where  $K$  and  $m$  are constants. For most organics  $m$  is found to be about 0.725 and  $K$  depends on the specific material. Figure 6 shows Cair's data<sup>18</sup> for Kapton and the Matskevich data for Teflon fitted to Eq. (12).

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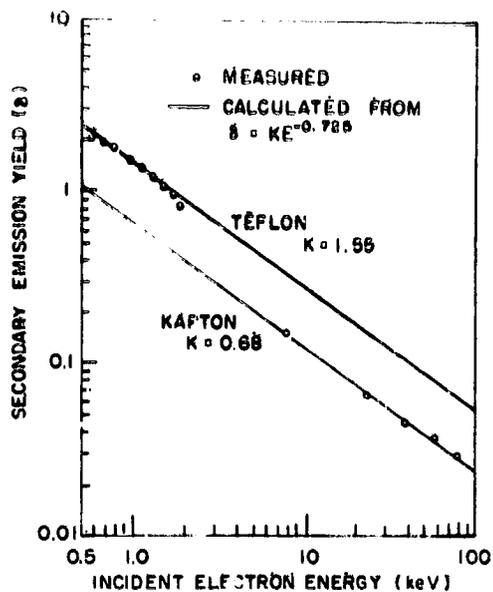


Figure 6. Plot of Empirical Relationship [Eq. (12)] Between Secondary Emission Yield and Incident Electron Energy for Teflon and Kapton. Measured values taken from References 17 and 18

The angular dependence of secondary emission follows the semi-empirical relation

$$\delta_{\theta} = \delta_0 \exp c (1 - \cos \theta) \quad (13)$$

where

$\theta$  = angle of incidence of electrons with respect to the surface normal,

$\delta_0$  = secondary emission coefficient at normal incidence,

$\delta_{\theta}$  = secondary emission coefficient for electrons incident at angle  $\theta$ .

The constant  $c$  is determined empirically. For most polymers we have found  $c \sim 2$ .

## 5. BACKSCATTER

Since information on backscatter is needed for most secondary emission measurements, data on backscatter is about as extensive as for secondary emission. Theoretical and empirical relationships have also been developed for the calculation of backscatter coefficients.

For most of the available data, the following empirical relationship holds:

$$\beta = AE^{-m} \quad (14)$$

where  $\beta$  is the backscatter coefficient, E the incident electron energy and A and m are constants. For the polymers, we have found that A = 0.1 and m = 0.2 fit most of the available data fairly well.

The backscatter coefficient,  $\beta_\theta$ , for electrons incident at angle  $\theta$  to the surface normal was found by Darlington<sup>19</sup> to be given for metals by

$$\beta_\theta = B(\beta_0/B)^{\cos \theta} \quad (16)$$

where  $\beta_0$  is the coefficient at normal incidence and B a constant. This expression also fits the polymer data taking B = 1.

## 6. ELECTRON RANGE AND RATE OF ENERGY LOSS

There have been numerous measurements of electron range and rate of energy loss for electrons with energies above 10 keV. Many empirical relationships for the calculation of range have been published and reliable theory has been developed for calculating both range and rate of energy loss above this energy. Computer generated tabulations, such as that by Berger and Seltzer,<sup>20</sup> based on the theory are available. For electron energies below 10 keV, however, there have been relatively few measurements and theoretical procedures have not been fully developed and tested.

Ashley et al are investigating electron range and energy loss for energies below 10 keV under a contract with RADC/ETS (formerly AFCRL/LQ). A report<sup>21</sup> on this work containing a tabulation of range and rate of energy loss in aluminum and aluminum oxide for electrons with energies down to 1 eV is available. The work is being continued to cover other materials including polymers.

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20. Studies in Penetration of Charged Particles in Matter, National Academy of Sciences-National Research Council, Washington, D. C., Publication 1133, 1964.
21. Ashley, J. C., Tung, C. J., Anderson, V. E., and Ritchie, R. H. (1975) Inverse Mean Free Path Stopping Power, CSDA Range and Straggling in Aluminum and Aluminum Oxide for Electrons of Energy  $\leq$  10 keV, AFCRL-TR-75-0583.

## 7. DIELECTRIC BREAKDOWN

Although many experimental and theoretical studies of dielectric breakdown have been performed, it is difficult to obtain a consistent view of the phenomenon from the literature. Repeated measurements of the dielectric strength of a given insulating material, performed by the same laboratory using a single procedure, can give results differing by an order of magnitude or more. This variability is probably due to minute structural differences (such as thickness variations, internal gas pockets, variations in microcrystalline structure, etc.) between samples. Differences in ambient conditions and measuring techniques also have significant effects on the results obtained.

The lack of consistent data on dielectric breakdown has made progress in the development of theories that can be used to explain and analyze the breakdown process very difficult. Some progress has been made in developing a theory for dielectric breakdown in thin films of inorganic insulators such as silicon dioxide, but very little has been accomplished in explaining breakdown in polymers. Structural changes, both microscopic and macroscopic, that occur in polymers under electric stress make analysis of the breakdown process very complex. Much more work is needed in this area.

## 8. CONCLUSION

A considerable amount of information related to electron interactions and material properties involved in charge buildup in insulators is available in the literature. Although all of the parameters needed in this area for analysis of the spacecraft charging problem may not be available in the open literature, much progress has been made in this direction. Perhaps the most significant finding is that, after some evolutionary errors, techniques have been developed for the measurement of those parameters that may be needed but for which data is not already available. Theoretical procedures for the analysis of the charge buildup process have progressed along with the measurement techniques and, although some refinements may still be needed, they are much more reliable than those available a few years ago. These developments have resulted from a renewed interest in the conduction and charge storage properties of polymers and other amorphous insulators. Most of the available information on these factors have been generated during the past ten years. In fact, about 60 percent of the relevant material found in the search was published during the past four years. If this trend continues, much of the information needed to evaluate insulating materials for use on spacecraft may soon appear in the literature.

There are areas where the literature did not indicate adequate progress. As pointed out earlier, much more work is needed on the dielectric breakdown processes in polymers. Relatively little work has been done on the effects of ambient conditions on parameters such as carrier mobility, trapping cross-sections, etc., and the changes in material properties related to charge storage that could occur, particularly in polymers, during prolonged exposure to high vacuum, cryogenic temperatures, low energy electrons and other environmental factors that may be encountered in space.

Although the open literature contains a very good base of information, only data taken on specific satellite insulating materials under controlled conditions and with particle spectra similar to the space environment can properly test the value of this information in relation to the problem of spacecraft charging.

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Following is a partial list of references covered during the literature search. Some of the references given in the text are also repeated here for the sake of completeness. An attempt has been made to select books and review articles where possible to minimize the number of references. Many of the references contain a variety of information and in that sense their classification into categories is somewhat arbitrary.

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